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Coal seam gas and associated water: A review paper

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ABSTRACT

Coalbed methane (CBM) or coal seam gas (CSG) as it is known in Australia is becoming an increasingly important source of energy around the world. Many countries such as United States, Canada, Australia and China are investing in the CSG industry. A rise in the cost of conventional natural gas and many other energy resources, along with a decline in these conventional resources and issues such as climate change have encouraged a global interest in alternative sources of energy like CSG. The estimated quantity of CSG worldwide is around 1.4×10^{14} m^3, it is clear that coal seam gas is a significant source of energy. The first section of this paper will discuss the production size of CSG worldwide and the future of the industry. The usage of the coal bed seam for the sequestration of CO_2 is also an added benefit. The reduction of CO_2 released to the environment may help in the future mitigation of global warming. In addition, the re-injecting of the co-produced CO_2 enhances the commercial recovery and production of CSG wells. In the second section, the impact of the CSG industry's by-products on the environment, the freshwater ecosystem and human health are analysed. The second section includes issues associated with the large volume of co-produced water with undesirable composition in the CSG industry. The management of this enormous amount of water requires cost effective technologies and methods. Many methods for dealing with water problems are discussed and analysed in this paper.

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1. Introduction

Coalbed gas (CBG) or coalbed methane (CBM) is a form of natural gas extracted from coal beds of both low rank and high rank coals. CBG is an important energy resource because of the increasing demand for gas as a substitute for coal and oil in electricity generation [1]. The coal seam gas (CSG) industry is relatively new in the history of the energy sector with only around 30 years of commercial production [2]. The United States is the top producer with 70–80% of world production. Australia is the next highest producer with a 14 year production history followed by Canada, China and India. These countries extract natural gas from shallow to medium depth coal seams and also from coal seams in advance of or during coal mining [1].

The CSG refers to adsorbed gas, in this instance methane, in a near-liquid state inside the pores within the coal. CSG is also called sweet gas because it is free of hydrogen sulphide. The open fractures in the coal can also contain free gas or can be saturated with water [3]. Production of CSG is achieved by reducing the pressure within the coal seam that releases the methane from the coal in the form of gas. The methane is brought to the surface accompanied by the CSG water as the pressure is released [4].

The energy crises in the 1970s were responsible for serious studies evaluating the production of the CSG for commercial use. Successive research on the origin, accumulation, distribution, availability, and recoverability has been carried out during the past two decades [5]. The rise in extraction and remediation costs of coal production, along with climate change has encouraged the global interest in alternative sources of energy. Worldwide, coal seam gas is a major source of energy that is estimated to be around 256 Tm^3 (Table 3). As conventional gas sources decline, unconventional sources of gas, like coalbed methane (CBM), will gradually become increasingly important in many countries [6].

The importance of coal seam gas as an energy source, as an example in Australia, can be shown in Table 1. The table shows that coal seam gas contribution in the energy production is higher than petroleum products (oil, condensate and LPG) individually. It also represents approximately 11.5% of the total need for gas energy in Australia. Under current production rate coal seam gas is expected to last for 100 years which is higher than petroleum products, black coal and conventional gases [7].

Coal seam gas (CSG) is mainly a combination of methane (CH_4) and carbon dioxide and has very close methane percentage (95%) to that of natural gas (NG) (97%). In contrast biogas produced form digestion process has methane content around 68% which makes it low energy content as shown in Table 2. Due to the decline in the NG resources and the low quality of biogas, CSG can be the energy resource solution for the next few decades. This can be true until the technology be able to enhance the production of biogas from anaerobic digestion process and reduce the cost of purifying the gas.

The aim of this paper is to address many aspects regarding the coal seam gas such as production worldwide, its impact on the environment, its benefit and the impact and management of the associated water. This paper also addresses the different methods that have been applied to control the negative impact of the produced water when used for irrigation.

2. Coal seam gas resources and productions worldwide

The estimated world coal seam gas resources in place are around 10.2 million PJ (256 Tm^3) as shown in Table 3. The majority of these resources are in the former Soviet Union, North America, and the Asia Pacific. Coal seam gas is produced in many

Table 1
Coal seam gas as a source of energy in Australia compare to other sources [7].

Energy source	Unit	Amount	Ratio of economic demonstrated reserves (EDR)
Coal	PJ		
Black coal	PJ	987,064	111
Brown coal	PJ	359,870	539
Petroleum	PJ		
Oil	PJ	6,290	10
Condensate	PJ	12,691	45
LPG	PJ	4,399	42
Gas	PJ		
Conventional gas	PJ	123,200	68
Coal seam methane	PJ	16,180	100
Uranium	PJ	685,440	141

Table 2
Compositions and potential energy contents of methane-base gases [8,9].

Gas type	Composition	Energy
NG	97.0% CH_4 2.2% C_2 0.3% C_3 0.1% C_4+ 0.4% N_2	11.3 kW h/m^3
Coal seam gas	95.0% CH_4 3.0% CO_2 2.0% N_2 Ethane trace	9.96 kW h/m^3
Biogas	68% CH_4 26% CO_2 1% N_2 0% O_2 5% H_2O	7.5 kW h/m^3

Table 3
Coal seam gas statistics in 2008 [10].

	Unit	Australia	World
CSG resources	PJ	168600	10240000
	Tm^3	4.3	256
Share of the world	%	1.6	100
CSG production	PJ	139	2700[a]
	Bm^3	2.8	65.1
Share of the world	%	5.1	100
CSG share of total gas production	%	8.4	5.0

[a] Estimate includes United States, Canada and Australia only, P=Peta 10^{15}, T=Tera 10^{12}, B=Billion 10^9.

countries, with the United States, Canada, Australia, India and China predominating [10].

The size of the CSG industry around the world can be categorized by the main producers; the following are the top producing countries;

2.1. United States

The US has a majority share of the mature coalbed methane market in the world. Throughout the past two decades, CBM production in the US increased dramatically, up to 49.7 Bm^3 in 2007, accounting for 9.1% of total natural gas production in the US [11]. The largest coalbed methane gas development project in the United States is located in the Powder River Basin [12]. There are nearly one million oil or gas wells in practice in the US [13]. The first coalbed well was drilled in the BlackWarrior Basin in the US in the mid 1970s, and commercial production began in 1980. Today, there are more than 4650 active CSG wells in the US, and the cumulative gas production now exceeds 52 Bm^3. The Powder River basin currently ranks third globally in coalbed methane production [14]. In 2002, the US Geological Survey (USGS) assessed the technically recoverable, undiscovered coalbed-gas resources in the Appalachian basin and Black Warrior basin to be about 472 Bm^3 [15].

2.2. Australia

Australia has rich deposits in Queensland where it is known as coal seam gas (CSG). Coal seam gas (CSG) offers remarkable economic potential for Australia. The estimation of the industry in the longer term of the overall production for the domestic market will be around 200 PJ per year. The export of liquefied coal seam gas will increase production by no less than a factor of ten [16]. Australia started production of CSG commercially in the mid of 1990s in Queensland. Since then, this industry has developed very rapidly, with 90% of the CSG production from Bowen and Surat Basins coal field in Queensland. The estimated resources of CSG are 4.3 Tm^3 and the production was about 2.8 Bm^3 in between the years 2007 and 2008. Currently the production has risen approximately to 6.2 Bm^3 [17,10].

2.3. China

The CSG development in China has increased significantly through the past decade. Until 2003 there were only 250 documented CSG wells, however this number increased to 2500 wells in 2008 [18]. The total CBM resources present in China in Huaibei and Huainan coalfields exceeds 1.4 Bm^3 [19,20]. CBM in China represents a very promising source of energy and some studies recognize the geological CBM resource volume as third in the world behind the United States and Canada. There are nine major CBM basins in China, their total reserve is 30.9 Tm^3 which is 84% of the total resources in China [21]. In recent years, natural gas demand in China has grown significantly due to the rapid and continuous growth of its economy. Over the past 30 years, China's natural gas consumption has increased from 12.1 Bm^3 in 1977 to 67.3 Bm^3 in 2007. This Chinese growth represents an increase of 456% and an average annual growth rate of 5.2%. A projection by the International Energy Agency (IEA) showed that China's natural gas demand will elevate to 110–120 Bm^3/year [11]. The projection for China's future demands of CSG show that it will grow faster than anywhere else [22].

2.4. Canada

Canada has over 19.8 Tm^3 of CBM gas resources comparable to the U.S. resources. The production of CBM has estimated to grow to 56–85 $\times 10^6$ m^3 over the next 10–20 years and lead to the recovery of up to 2.1 Tm^3 of gas. Canada now has the world's largest coal storage, since 2000, drilling activity increased and led to over 3000 CBM wells and was estimated to grow considerably in 2005 and beyond. CBM will become an increasingly important part of the gas industry in Canada [23].

2.5. Europe

In Hungary the coals of the Mecsek Basin contains large quantities of coalbed gas that is largely methane. Two preliminary estimates of the total gas content of the coalbed are between 28 Bm^3 and 113 Bm^3 [24]. In the Ruhr Basin in Germany, 77 power stations with a total of 70 MW are using CSG to generate 650 GW h of energy. The plant consumed about 280×10^6 m^3 of coal gas in 2002 [25]. The Central Asturian Coal Basin, located in Northern Spain, is the most important coal basin, the gas content in the coal basin has been estimated to be a minimum value of 25 to 100×10^6 m^3 [26].

2.6. India

India in last few years has had an intensive exploring and developing of its CBM resources through international tendering processes. Commercial production is believed to have been just over 0.056 Bm^3 in 2009 [20].

2.7. Indonesia

Indonesia has highly prospective CBM potential, with an estimated 12.8 Tm^3 of in-place resources located mainly in Sumatra and Kalimantan provinces. Indonesia's coal seams have low-moderate gas content and of relatively low thermal rank (sub-bituminous) [27].

2.8. United Kingdom

It was forecasted that in ten years' time UK coal bed methane (CBM) industry should be producing 20% of the UK's gas production. The UK CBM resource is estimated to be 2.9 Tm^3 of which 0.14–0.28 Tm^3 should be developed this decade [28].

Table 4 summarizes the production of CSG in the world with United State dominating by producing ~80% of the world CSG.

The economic evaluation preliminarily shows that coal bed gas could be produced with cost levels between 5 and 6 US dollars/GJ, compared to expected natural gas prices of about 4 US dollars/GJ in the medium to long term [29]. Coal seam gas wells are cheap because they are usually shallow. Deeper wells tend to have lower coal permeability and productivity [30]. It is obvious that the production of the CSG is increasing rapidly and more countries are entering industry.

3. Impact of the CSG on environment

Coalbed methane has become an important source of energy in many countries. The rapid development in this sector has resulted in substantial pressure on communities to deal with its environmental consequences. The rate of production of CSG has increased dramatically during the last decade as shown in Fig. 1. It is obvious from Fig. 1 that the production has increased almost by 120% [31]. The exploration and development of coalbed methane brings a series of environmental issues because of unsuitable exploitation activity [32]. The main environmental problems are the effects of the development of CBM on water resources, atmosphere, vegetation, land, and habitation [33,34]. Even though the production of CSG represents a very important source of natural gas, there are concerns over potential negative environmental impact on shallow groundwater resources [32]. The leakage of fluids and gases from the CSG operation may contaminate this valuable water resource [35].

3.1. Emission of gases

A major environmental impact of the CSG is the emission of methane and carbon dioxide gases to the atmosphere. Methane is recognized as a greenhouse gas (GHG), and it is likely playing a significant role in global warming. Methane is more effective in trapping heat in the atmosphere by more than 20 times than carbon dioxide. Coal seam gas (CSG) emissions contribute a large volume of methane gas to the atmosphere [36]. Coal seam gas is also associated with high levels of carbon dioxide that can reach 50% in some basins. Australian coal seams are known to be dominated by CO_2 gas in some places and in some others by CH_4 or even in many instances both CH_4 and CO_2 are presented in varying proportions [17]. The amount of carbon dioxide co-produced with the CSG represents a real problem to the global environment.

Table 4
Summary of CSG from the stated country.

Country	Production in Bm^3
United State	52
Australia	6.2
China	1.4
Canada	0.85
India	0.056
Europe[a]	4.6
Total	+65.1

[a] Estimated (65.1 Bm^3–50.5 Bm^3).

3.2. Associated water

Coalbed methane production results in large quantities of water that are released as by-products of production. The production of methane from coal seams sometimes requires pumping water from the well up to six months or more before the gas is produced [37]. This water, in some cases, may damage the surface water quality, underground water, and the overall ecosystem's balance. Conflicts sometimes arise because in some countries like Australia, surface owners may not own the mineral rights underneath their property and are required to cooperate with development that may disrupt the use and control of their land [38–40]. High levels of salinity can affect the vegetation's ability of withdraw water from soil, the accepted level of salinity for irrigation is around 3 dS/m. In addition to the negative effect of sodicity on the soil structure, high levels of Na^+ may cause a reduction in Ca^{2+} and Mg^{2+} in the plants if used for irrigation [41]. Irrigation with water of high Na concentration may affect the soil properties such as soil infiltration, permeability and aggregate stability. Thus high sodium will significantly affect the plant growth [42].

The development of CBNG has negatively affected fishery resources. The concentration of metals and trace elements in CBNG produced water in some basins exceeds the standards set for aquatic life. When fish are exposed to some materials that are usually found in CBNG produced water such as $NaHCO_3$, harmful effects have been reported [43]. The sodic-salty associated water from CSG is a major contributor to landscape salinity and alkalinity in Warrego, Paroo and other places in western catchments of Australia [44].

The characteristic of CSG water has been studied [37] for the Liulin basin in China. The study about Liulin showed high content of chlorine in addition to the salinity–sodicity of the water, the standard for irrigation is no more than 250 mg/L, which may cause elevation in soil salinity, loss of crops, damage to vegetables and desertification. The high level of chlorine results from using chloride-base drilling and fracturing fluids that come to the surface with the produced water. Furthermore heavy metals and

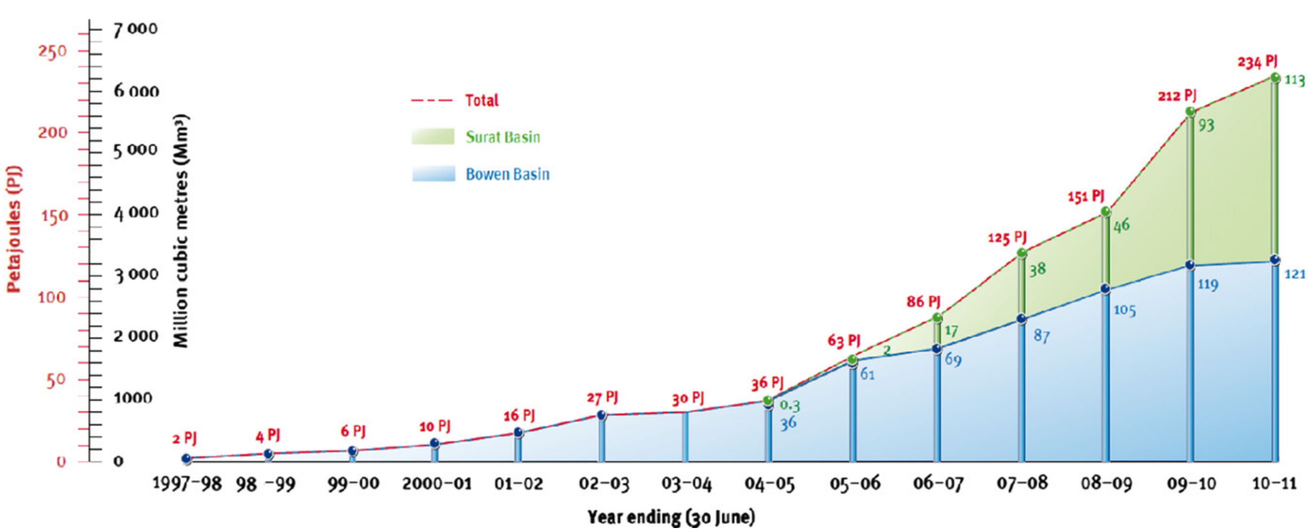

Fig. 1. The production of coal seam gas in Queensland—Australia from 1997 to 2011 [31].

ammonium nitrogen (NH_4–N) in the CSG produced water is higher than that permitted for drinking water.

Discharge of the co-produced water with CSG extraction into retention ponds and small transient channels have dramatically affected the ecological and environmental conditions in the Powder River Basin. The discharged produced water has affected both surface and groundwater quality in the region due to its high concentration of sodium, bicarbonate and trace metals [45].

The organic composition of the co-produced water from CSG in the Powder River Basin, WY, is reported as a potential health and environmental concern. The organic compounds identified in the samples from the CSG produced water included: phenols, biphenyls, N-, O-, and S-containing heterocyclic compounds, polycyclic aromatic hydrocarbons (PAHs), aromatic amines, various non-aromatic compounds, and phthalates. Many of these organic compounds such as phenols, heterocyclic compounds, and PAHs are most likely derived from coal. Some of the organic compounds identified in the produced water samples that may find their way to the ground water are potentially toxic, but at the levels measured in these samples, are unlikely to have significant health effects [46].

4. Environmental benefit of the coal seams

Fossil fuels are the main fuel source for most countries and are continuing to grow to satisfy the significant increase in electricity demand. Coal is the cheapest fuel source in the world. Over the past two centuries, coal has played a significant role in world economic growth and stability. Burning coal at power plants is the main emission source of carbon dioxide into the environment. In addition, carbon dioxide is produced in large quantities along with methane from the coal seam gas [17]. Coal seams in Australia are known to be dominated by carbon dioxide. Ironically, coal may also play a role in reducing the carbon dioxide emission to the environment. Carbon dioxide can be stored in the coalbed reservoir while enhancing the commercial recovery and production of coalbed gases [6,30,47].

Recently the injection of CO_2 in deep and unminable seams has become an active research area. The CO_2 sequestration in enhanced coalbed methane/gas recovery (ECBM) during injection of Carbon dioxide has offset the cost of this natural gas [48]. The characterization of coal is essential for sequestration of CO_2 and developing coalbed gas recovery process [49]. In most cases, coal contains free water in the cleats, as well as moisture which is an important part of the coal structure. Most natural gas production starts with removing water from the coalbed to initialize the gas recovery. Carbon dioxide injection may change the coal wetting behavior because CO_2 has a strong affinity to coal [3]. Carbon dioxide adsorption on both dry and water-saturated coal is much more rapid than CH_4 adsorption and replacement of CH_4 by CO_2 is faster than the reverse process. These factors clearly have a positive effect for CO_2 enhanced coalbed methane production and CO_2 sequestration [14,50]. A study in Japan [51] showed that the injection of CO_2 in to a coal seam gas has significantly enhanced methane gas production. Also, the study has found that the water production rate was not clearly affected.

With ECBM, CO_2 or flue gas, a mixture of carbon dioxide and nitrogen can be injected and stored into a coal seam to replace the adsorbed methane. A significant advantage is that the revenue from methane production can offset 50% of the costs associated with CO_2 capture and storage [52]. As long as a hydrostatic head is maintained and sealed, the adsorbed CO_2 will be stored for geological time scales in a known geographical area. Another study [53], illustrated that the recent estimates of the worldwide CO_2 storage capacity of coal seams is between 225 Gt and 300 Gt. In 2005 the CO_2 storage capacity of deep coal seams in Australia was estimated at 5.2 Gt, considering only the areas that have been discovered and certified.

The Huntly coalfield in New Zealand has a significant coal deposit with relatively low to moderate methane gas content of 2–4 m^3/t. Despite the low methane content, the CO_2 capacity holding is relatively high around, 18 m^3/t compared to CH_4 at the same pressure [54]. The separation of CO_2 from flue gas and injection into the unminable coal zones of the Powder River Basin seam, can increase recovery of methane by 17% and can sequester over 86,000 t/ac CO_2. However the CO_2-baded process is currently uneconomical because the cost to separate CO_2 from flue gas is the major cost driver associated with CO_2 sequestration. Using existing commercial separations technology, the cost to separate CO_2 from flue gas is currently \$42/t CO_2 [55]. The commercial-scale sequestration of carbon dioxide into deep, unmineable coal seams, with a continuous recovery of methane, has been successfully applied at Burlington Resources in New Mexico [56].The cost of sequestration of CO_2 in coal seam beds will be around 2.84 to 28.12 dollars per metric ton, depending on the type of geological formation [57].

The geological storage of CO_2 in saline aquifers mostly relies on the sealing characteristic of the cap rocks. A sealing of coal seam above the saline aquifer such that in Gippsland Basin, Australia and Münster Cretaceous Basin, Germany is preferable because the coal seams may act as a barrier for upward CO_2 migration. The attractive aspects are that coal has a strong capability to adsorb CO_2, has low permeability and coal tends to swell due to adsorbed CO_2 [58–60] which lowers coal's permeability. These aspects reduce the leakage of the CO_2 and increase the storage capacity of the aquifer [61]. Low ranked coal may be another option for sequestration of CO_2 because of the high CO_2 adsorption and high permeability. Low ranked coal is also known for low methane content which makes it uneconomical for production of CSG [62].

Despite the potential economic and environmental benefits of sequestration of CO_2 gas in the coal seam, there are many unknowns in our understanding in this field. Some of these gaps are; the uncertainty of the coalbed geological formation volume, the fate and stability of the CO_2 in the coalbed, and the consequences of the reaction of CO_2 with water to form H_2CO_3 which can then migrate out of the seam. There are of course vast opportunities for further research in this field [56].

5. CSG co-water characteristics and chemical composition

5.1. Major components in CSG co-water

The composition of the CSG co-water has been analyzed at different basins around the world in order to understand the impact of such water on the environment. In a study by Dahm et al. [63] a geochemical data base was created with 3255 CBM wellhead entries from four basins in the Rocky Mountain region. The Rocky Mountain study employed 64 parameters and constituents. The major components in the CBM associated water in the Rocky Mountain study were sodium, bicarbonate, and chloride which accounted for more than 95% of the total ions on average for each basin. The CBM water from the Rocky Mountain fell mainly into either sodium bicarbonate or sodium chloride type depending on the basin location.

The concentration of the components in the CBM water differed slightly due to the site basin and location as shown in Table 5. This table shows the composition of CSG associated water from Bowen Basin in Queensland and different basins in United States. In general, for both locations the CSG associated water pH

Table 5
The CSG associated water composition from Bowen Basin in Queensland, Australia and different basin in United States, approximately determined from different figures [64,65].

Country	Basin/location		Calcium (mmol/L)	Magnesium (mmol/L)	Sodium (mmol/L)	Chlorine (mmol/L)	SO_4 (mmol/L)	Bicarbonate (mmol/L)
Australia	Bowen Basin	Durham Ranch	0.35	0.4	100	70	0.85	12
		Fairview	0.015	0.04	11	6	0.05	10
		Upper seam	1.25	1	100	80	0.005	10
		Lower seam	0.75	0.65	100	80	0.01	20
USA	Black Warrior Basin		0.65	0.5	70	55	0.05	10
	San Juan Basin		0.7	0.6	300	60	0.075	300
	Uinta Basin		1.35	1.3	160	100	0.05	70
	Maramarua C-1		0.15	0.05	10.5	4	0.05	7

are high and they have relatively high alkalinity (7–300 mmol/L as $CaCO_3$). Calcium and magnesium concentrations are comparatively low (0.015–1.35 and 0.05–1.3 mmol/L, respectively and sulphate levels are very low in some places (0.005–0.85 mmol/L). The highest concentration for sodium and chlorine are 10.5–300 and 4–100 mmol/L, respectively. There is a significant difference in magnitude between major ions (sodium, chloride and bicarbonate) and minor ones (calcium, magnesium, and sulphate). For example, concentrations of sodium are about 222 times higher than calcium, and concentrations of chloride are more than 117 times higher than sulphate in some places [44,64,65].

5.2. Trace components in CSG co-water

The chemical composition of the water associated with the CSG production is poor quality and carries potential environmental concerns [66]. CSG water also contains small amounts of trace metals that accumulate in the retention ponds over time. The ponds within the Powder River Basin of Wyoming showed high concentration of arsenic. The maximum arsenic concentration detected of 146 μg/L, and this level can create a potential pollution for the groundwater. EPA has set the arsenic standard for drinking water at 0.01 ppm. The high concentration of arsenic in the pond was due to the semi-continuous input of CSG produced water with low concentrations of 0.2 μg/L to 0.48 μg/L. Because of reduced infiltration and high evaporation rates, arsenic became concentrated over time. The low infiltration was due to the high sodium concentration and high sodium adsorption ratio of the CSG produced water that eventually led to disruption of soil structure [67]. In addition to these components, the co-produced water from CSG in PRB in Wyoming also consisted of dissolved methane between 0.5 mg/L and 89 mg/L [68].

The co-produced water in the Powder River Basin, USA, recently specified another chemical species in addition to the common chemicals. Inorganic nitrogen in the form of ammonium has been detected in the discharged water from the Powder River Basin. Despite the fact that ammonia is stable under the conditions that persist in subsurface coals, once it is released at the surface it becomes exposed to atmospheric oxygen and changes composition. The microbes at the surface obtain energy from aerobic ammonium oxidation (nitrification) that produces nitrite in the first stage and then eventually nitrate, both nitrite and nitrate are detrimental to aquatic ecosystems [69]. A model conducted by [59] to predict the changes in the water quantity and quality along the Powder River Basin main stream showed that the development in the CBM negatively affected the stream water quality that showed an increase in the stream flow rate, water temperature and salinity. Many organic compounds were identified in the CBNG produced water such as phenols, biphenols, N-, O-, and S-containing heterocyclic compounds, polycyclic aromatic hydrocarbons, aromatic amines, various non-aromatic compounds, and phthalates. These organic compounds have been identified as a potential health and environmental issues. Powder River Basin was among wells that contained numerous extractable of organic compounds [46]. Shallow CSG groundwater in the PRB had dominated with high levels of calcium and sulphate (5200 μmol/L and 2370 μmol/L, respectively) that may be due to gypsum dissolution and pyrite oxidation. In contrast, deep CSG ground water is dominated by sodium and bicarbonate. Microbial actions are behind the increase of bicarbonate and decrease of sulphate in the deep water [66]. The change in the chemistry of CBNG discharge water as a result of reaction with semi-arid ephemeral channels in PRB, Wyoming was measured. Significant changes were observed for Fe, Mn, and As; and seasonally for B. Dissolved Fe and Mn decreased, while As and Se increased in downstream channel flow [70].

Two studies [71,72] showed that the CBM associated water has no consistent trends in trace elements concentration. Generally, dissolved Al, Fe, As, Se, and F concentration increased due to increase in the water pH of the holding ponds. Dissolved Ba, Mn, Cr, and Zn concentration showed a significant decrease in the holding pond water due to the precipitation of barite, rhodochrosite, chromium hydroxide, and smithsonite. For example, dissolved Ba and Cr concentrations decreased by 46.6% and 35.04%, respectively.

Due to the maturity of shale rock, along with its high organic content, shale can also contain very high levels of radioactive Radium 226. Once removed from its source rock deep in the earth and exposed to water and air, radium starts to decay rapidly and has a half-life of 1600 years. The decay product of radium is radon gas. Radium is over 1million times more radioactive than the same mass of uranium [73].

6. Management of CSG associated water

6.1. CSG co-water quantity

A recent study by the Coal Industry Advisory Board (CIAB) estimated global methane emissions from the world coal industry to be at 25 million tons per year. Around 4.3 million tons (17%) of this is recovered and only 2.0 million tons (8%) are actually utilized [74]. This amount of coalbed gas is accompanied by a large amount of water. Gas and water production from a coal deposits can be divided into three distinct stages. In the first, the rate of gas and water production is approximately constant. The second stage starts once pseudo steady state is reached, it can be distinguished by the decline in both gas and water production rate. The third stage begins when the gas rate reaches its maximum. This final stage is characterized by a slight decline in gas rate and negligible water production. Water production, depending on the geological formation of the basin, can continue for approximately 15 years [75]. The final stage covers most of the economic life of a coal well [76].

6.2. Current managements

Management of large volumes of associated water with CSG production is a potential concern due to the elevated water salinity and sodicity. The produced water is managed in different ways in different states in the United State and offshore. While large portions of the onshore produced water, if applicable, is re-injected for enhanced gas recovery, the remaining portion is directly disposed to the environment. Much of the offshore produced water is directly discharged to the ocean [13]. Land application of the onshore CSG associated high saline–sodic water is a common management method that has been practiced in the Powder River Basin of Wyoming and Montana. The irrigation of lands with the co-produced waters from CSG is one management option. However the use of produced water for irrigation can result in deterioration in soil quality and changes in physical and chemical parameters of the soil. One study [77] has shown that irrigation with slightly saline water is a possible option. The irrigation method of the produced water from coal bed has to be applied at a rate to maintain soil moisture at field capacity. A preliminary short term greenhouse study has showed the growth of sorghum-Sudan grass is optimized when irrigated by CSG associated water of total dissolved solids of 2000 mg/L [77].

6.3. Discharge to surface water and re-injection

Surface water is the first choice for discharging the coal seam gas associated water. The impact of the sodic-salty water from CSG on the environment can be mitigated by reinjection of it into the depleted coal seam. Reinjection will refill the coal seam well and lower the need to draw groundwater from long distances [78].

6.4. Use for irrigation

Two problems associated with irrigation by CSG co-water are sodification and salinization of soil. Salinization refers to accumulation of salt at the plants root levels while sodification refers to accumulation of Na on the cation exchange complex of soil. These problems become more destructive in dry climate where evaporation rates speed accumulation of salt on the surface [79]. The associated waters with the CSG industry are used to irrigate crops such as barley and alfalfa. It has been shown by many studies that irrigation with water with an electrical conductivity (EC) greater than 1.0 dS/m and sodium adsorption ratio (SAR) values above 10 can result in soil degradation and salt accumulation [80].

These two important parameters EC and SAR that assess the quality of the water produced from CSG industry are salinity and sodicity. The two parameters can be measured by EC and SAR, respectively. The total soluble ion concentration in water represents the salinity and the ratio of the sodium ion to the summation of both calcium and magnesium ions represent the SAR. The sodium adsorption ratio can be represented by this equation $Na^{+}/[(Ca^{2+}+Mg^{2+})/2]^{1/2}$, in milliequivalents/l [$mmol_c/L$] [41].

In one study [81] the change in chemistry of soils irrigated with the CSG water collected from Powder River Basin of Wyoming and Montana was compared with non-irrigated soils. Coarse-textured soils were detected in the irrigated soil in contrast to fine-texture for the non-irrigated soil. The application of the CSG water significantly increased soil EC, SAR, and ESP values to 21, 74, and 24 times, respectively compared to the non-irrigated soils. The coarse-texture of the soil was due to the salinity build-up. The irrigated soil suffered a significant build-up of sodium as well as sodium mobilization through the soil contour [82]. Another study [83] for the same location showed that the change in the chemical composition also affected the bulk density, infiltration and Darcy flux rate at various depth intervals to 120 cm. The study showed over multiple-year applications that the soil EC and SAR values increased to depth 30 cm which led to reduced surface infiltration and lowered Darcy flux rate to 120 cm. Furthermore, in regards to PRB location, a study by [84] was carried out to illustrate the direct or indirect effect of the CSG produced water on changing of stream water quality of Powder River. The results indicated that the CSG development negatively affected the water quality in the Powder River. The stream had elevated sodicity indicated by a significant increase of the sodium adsorption ratio [84].

The effect of irrigation water with SAR as a low as five will have a negative effect on the soil structure and infiltration rate. Reservoir storage of the CSG associated water resulted in an increase in pH, EC, TDS, alkalinity, SAR and sulfate whereas calcium decreased significantly [85]. The release of the CSG water to the land may cause precipitation of calcium carbonate in soil that may cause a reduction in the infiltration rates and increase runoff and erosion [86].

7. Treatment of CSG water

The treatment of the CSG associated water is highly recommended before usage because of the damage it may cause to the soil and groundwater. Many methods have been suggested to overcome this problem, and a list of selected methods is shown below from published literature:

7.1. Common method

In common cases of dealing with CSG associated water and to protect the environment, the CSG industry uses a system of treatment and storage pond evaporators. To prevent leakage from these ponds synthetic membrane liners are used [87]. However the storage pond evaporator is an efficient solution, it may cause some environmental problems such as damage to the shallow groundwater in the area. The operators of CSG wells are usually augmenting in-stream discharge with deep underground injection. Injection helps to keep the cost at low levels without effecting the CSG operation [87]. The CSG co-produced water contains many components, among these is dissolved inorganic nitrogen (DIN), primarily as ammonium. It was found that this ammonium ion can be removed when given sufficient travel distance in a stream channel. One study [69] showed that nitrification and nitrite reduction was tested in a channel receiving water from a coalbed gas well in the Powder River Basin, Wyoming. The study showed that significant amount of the ammonium was oxidized after 50 m length of the downstream and 60% of the dissolved inorganic nitrogen was removed after 300 m of transport. While the stream channel may be effective for removing DIN associated with the CSG water, the fluctuation in the dissolved oxygen in the stream significantly affected this process. The authors do not suggest this process for a long-term treatment.

7.2. Amending the CSG associated water with chemical treatment

Amending the CSG associated water with chemicals to change its composition is one of the methods that have been addressed in literature. The water associated with CSG industry contains high levels of bicarbonate. Recently bicarbonate removal with sulfuric acid was suggested as a simple and a low cost method. The reaction kinetics between the sulfuric acid and bicarbonate was investigated as an attempt for treatment of alkaline water [88]. The kinetics study showed some key results that identified the removal of bicarbonate by the reaction kinetics variables.

However this method is contributing to reduction of the water pH, it did not prevent the build-up of salts and sodium in the soil when used in irrigation [83].

7.3. Treatment of soils irrigated with CSG associated water

There are many strategies in managing the salinity–sodicity of a soil that has been irrigated with wastewater such that from CSG production. These techniques include salt leaching, and the addition of gypsum.

Leaching was shown to be an effective method for reducing soil salinity, however it may lead to soil solution salt concentration decreases relative to Na concentration. Leaching may affect the structure of the soil, in addition, the leached salt may find its way to the shallow groundwater [41]. Adding Ca-rich materials can be used for the reclamation of sodic soils. The Ca will displace Na occupying exchange sites. Such material as gypsum ($CaSO_4 \cdot 2H_2O$) when applied to the soil helps to depress the negative impact of high Na concentration. Gypsum helps to increase the electrical conductivity of the soil and it displaces Na with Ca on the exchange sites. This exchange will lead to free Na ions and with excess irrigation it leaches below the rooting zone. Soil treatment with gypsum has not been shown to be effective in exchanging Na with Ca unless the SAR of irrigated water is higher than 6–12 $(mmol/L)^{0.5}$. Generally, gypsum and sulfur are applied to soils being irrigated with CBNG associated water to protect the soil structure and fertility [79]. The CSG water pre-treatment using a sulfur burner and gypsum resulted in reducing the soil pH, however it did not prevent the build-up of salts and sodium. Another study [83] showed that the CSG water management using the above methods are currently not as efficient as they were projected.

7.4. Adsorbent method

Saline–sodic water from CSG industry in Powder River Basin of Wyoming and Montana was used to test the ability of calcium-rich zeolite in removing the high sodium concentration [89]. The process is based on a cation exchange by passing the CSG water over calcium-rich zeolite bed. The zeolite bed reduced the salt content of the CSG water by 72% and sodium adsorption ratio (SAR) from 34 to 10 $(mmol/L)^{0.5}$. In another study [90], a zeolite calcium (Ca^{+2})-rich chabazite was used in a column. The study showed that (Ca^{+2}) is tightly held on chabazite adsorption sites which results in formation of clinoptilolite zeolites. The adsorption capacities of the two types of ST and BR-zeolites were 9.6 and 12.3 mg/g, respectively and have the ability to lower the sodium adsorption ratio of simulated CBNG water from 30 to an acceptable level of 10. The calcium rich zeolite can be modified from sodium-rich natural zeolite by replacing the sodium component with calcium [42]. These studies have shown that removing sodium using zeolite technology is a potential method for water treatment alternative to membrane treatment. Another study [42] used a local Na-rich natural zeolite (clinoptilolite) from Wyoming to examine its ability in treating CSG water. This natural zeolite went through Ca-modification to remove Na from CSG waters. This study showed that a metric ton of Ca-modified WY-zeolite can treat 60,000 L of CSG water by reducing the SAR from 30 to 10. The used zeolite can be regenerated using concentrated $CaCl_2$ solution. It has been found that natural Ca^{+2}-zeolite is a more cost-effective method of CSG co-produced water treatment [42].

7.5. Evaporation

Evaporation is another method for mitigating high salinity water treatment from a CSG well. In a study by [91] heat was used to operate a triple-effect evaporator. The heat was recovered from the gas compressors and waste heat from compressor drive engine. Unlike conventional natural gas wells, the coal seam gas reaches the wellhead at a low pressure which required compression near the wellhead to inject it into the gas transmission pipeline. Around 47% of the fuel energy provided to the compressor drive engine was utilized by the evaporators. The result of this study showed that the evaporator system could handle produced water to produce a gas ratio of 1.43 kg/m^3.

7.6. Bioremediation

Bioremediation involves growing green plants for altering the chemical composition of the contaminated soil or water. Salt-tolerant green plants can remove base cations such as Ca, Mg, Na and K from water and soil. These constituents of various salts can then be removed from the area either by animal consumption or harvesting [41]. One study [41] showed that irrigation of salt-tolerant plants with moderate saline–sodic water can reduce the post-irrigated saturated soil solution salinity and sodicity. The study found that one species of plant *Atriplex lentiformis* had the greatest effect compared to other species investigated [41]. Another method of using CSG associated water has been studied [16] showing that growing algae could be a suitable choice for making use of this water. Micro-algae have been suggested to be cultivated in simple open ponds of CSG water by making benefit of a combination of carbon rich CSG discharge water and agricultural waste. This process will produce algae as a base for bio-fuel production and at the same time will convert the agricultural waste into fertilizers. In addition, the waste biomass can be digested at a bio-refinery to produce methane. Furthermore, the process will result in CO_2 capture [16].

7.7. Irrigation of croplands

The salty-sodic CSG associated water can be used to grow some kinds of crops such as alfalfa. One study showed [92], that salty water could be used to irrigate alfalfa crops. Irrigation with such water did not have a high effect on the soil pH but the soil salinity and sodicity increased at depth below 30 cm when flood irrigated. The study suggested that long term irrigation required soil treatment with Ca to prevent excessive salt built up and to improve the soil permeability. CBNG water has been examined for irrigation croplands. Five waters and three different soil treatments were applied to evaluate the effect of these waters on soil properties [93]. Water treatment consisted of Piney Creek water (control), direct irrigation with CBNG water (EC of 1.38 dS/m and SAR of 24.3 $(mmol/L)^{0.5}$) with no treatment, CBNG water mixed with solution grade gypsum, CBNG water acidified using sulfur burner and mixed with gypsum and CBNG water mixed with Piney Creek water. Samples of soils were collected at a depth of 60 cm to evaluate the effect of these different water treatments on soil EC, SAR and sulfur content. Both EC and SAR increased significantly in all treatment combinations.

8. Evaluation of the treatment methods

The management of water from coal bed methane may be done using different methods. A study [94] that took place in Alaska, looked at different management methods of water from coalbed methane. The study evaluated five methods, these methods were direct discharge on to the surface, controlled discharge into streams, injection into underground wells, concentration of the water by a multiple effect evaporator, and using reverse osmosis to produce clean water. Considering environmental

regulations, cost of instillation and operations, the study showed the potential of some of these methods. Evaporation processes were found to be the best method to use, this conclusion was only applicable within Alaska.

Other research [88] has explored different methods to partially or comprehensively treat co-produced waters, including reverse osmosis, nano-filtration, ion exchange chromatography, electrodialysis reversal distillation, capacitive desalination and rapid-spray evaporation. Reverse osmosis was an effective method for removal of monovalent salts. High pressure was required to separate impurities from water through the porous membrane. In addition, RO is highly expensive when applied on a large-scale. Another method that uses membranes to separate impurities from water is nano-filtration. NF is capable of removing divalent salts at lower pressure than reverse osmosis. The limitation of NF is that it is used for low dissolved solid content water. Some technologies become very expensive when applied for large-scale applications such as ion-exchange chromatography and electrodialysis reversal desalination (EDR). The EDR consists of alternating layers of cationic and anionic ion exchange membranes. Dissolved salt ions migrate through the solution forced by an electrical current. This technology is highly efficient in removing the salt from the solution, however it is expensive due to the use of the chemical additives. Ion exchange chromatography involves the exchange of ions between two electrolytes immersed in the extracted water. Despite the fact that IX is very efficient in removing salt, distillation is a high energy consumer. Other new methods such as capacitive desalination and rapid spray evaporation are in the development process [88]. The different types of treatment of CSG associated water such as membrane [40], ion exchange, reverse osmosis and other similar types often require large and specialized industrial equipment that have high energy consumption and capital expenses. Processes with high energy consumption are economically and environmentally unfavourable. The cost of using such processes is around $1 M per GL of saline water. The by-products from the reverse osmosis process are having a high volume of brine which still requires disposal, at least 300 km from the well location [16]. Therefore, in order to treat the CSG co-produced water alternative, cost-effective methods are required due to the limitations of the conventional methods. Using renewable energy, for example in Australia, is another option to reduce the cost of the by-product water treatment due to availability of such resources [95].

It is worth to mention that in Queensland/Australia currently testing small-scale ion exchange processes treatment plants with total dissolved solids (TDS) input of about 5000 mg/L to produce water with a TDS of around 1500 mg/L. This water quality is suitable for irrigation and livestock. The process can also produce by-products from process of further value, such as liquid gypsum and commercial grades of salt [96].

9. Conclusion

Regardless of the environmental problems associated with the CSG production industry, it remains an important resource of energy. Its energy content is approximately 90% of NG and count for 256 Tm^3 gas resources in the world. At the current production rate, CSG may last for the next 100 years. However coal seam gas comes from underground at different proportions, it is mainly a mixture of methane (95%) and carbon dioxide (3%). In addition, a huge amount of undesirable water is associated with the gas during the whole period of production. The management of both the carbon dioxide and the co-produced water are adding an extra expense to the cost of the methane. Many studies suggest the sequestration of carbon dioxide into the coal seam. Sequestration will not only help to reduce the impact of CO_2 on the environment but also may enhance the gas production. The major components of the water associated with the gas are sodium, bicarbonate, and chloride. Different researchers have shown the destructive impact of this produced water when used for land irrigation or discharged to streams. This paper has addressed the different methods that have been applied to control the negative impact of produced water for irrigation. The complete treatment of the CSG co-produced water requires advanced technologies which come with expensive costs. Further research is needed to distinguish cost-effective and environmentally friendly methods.

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